

Salinity Assessment: Status and Spatial Distribution in Case of Ayni-qaqa Irrigation Scheme in Tigray, Northern Ethiopia

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ABSTRACT

In the arid and semi-arid areas, soil salinity can be a significant concern to soil properties and has detrimental effects on the environment, agroecosystems, and crop yield and quality. Small-scale producers around Ayni-qaqa irrigation scheme have been suffering from crop yield reduction and various investment losses, because of the spread of salinity problems due to the long-lasting intensive irrigation practices. Study was conducted to assess the level of salinity at the scheme. A total of 128 soil samples from four sites of the scheme were collected during both dry and wet seasons for salinity assessment. Quantitative analysis was conducted for 9 salinity parameters and compared with the globally acceptable limits. Although the variation between soil depths is not significant, it is witnessed that around 50% of the scheme is affected by salinity. The highest salt accumulation across the soil profile was observed during the dry season as compared to that of the wet season. Intensive irrigation during both seasons at site four led to high salt concentration as compared to the other sites. Hence, community-based participatory salinity management strategies; involving the local farmers, experts, and stakeholders by creating awareness could possibly be useful to reverse the salinity problems.

Keywords: Agricultural production; Arid and semi-arid; Depth; Electrical conductivity; Irrigation; Leaching; pH; Salinity indices; Sustainability.

1. Introduction

The main goal of agriculture is providing food and fiber needs to human beings and as the population grows so as their requirements. According to [1], the world population is exponentially increasing and may reach 9.3 billion by the year 2050, while producing very low crop yields due to the negative impact of different environmental pressures. Crop production in many low rainfall areas of the world has always been facing water shortage to meet crop demands [2]. The highly erratic rainfall pattern which is common in Ethiopia resulted in recurrent drought and food insecurity in the country [3, 4, 5, 6].

Therefore, to address the challenge caused by food insecurity and water scarcity, achieving food self-sufficiency by agricultural development through irrigation is important for arid and semi-arid countries [7]; and has been a priority for the Ethiopian government [8]. An estimation of 40% of global food production comes from the 20% of irrigated areas [9]. Nevertheless, irrigation also has created problems, such as land and water resource salinization, adverse socioeconomic and cultural effects, and environmental damage. The soil salinity problem that mainly occurs in arid and semiarid regions is a phenomenon when soils and water or water table rising to or close to the ground surface have excessive soluble salts concentrated to injure plants and hinder soil and crop productivity at different levels [10]. Poor water management coupled with intensive irrigation [11, 12, 13]; limited rainfall amount (<400 mm), and high evapotranspiration conditions [14] are the natural or anthropogenic actions that cause soil salinization. Furthermore, growers are being forced to use subpar groundwater for irrigation purpose due to a significant lack of high-quality water, which makes the salinity issue worse [15]. The use of land and water resources for agriculture in arid and semi-arid areas remains unsustainable [16] due to the inborn salinity nature of the land surface and the application of saline water for irrigation [17].

Up to 50% of arable land is predicted to be lost by the middle of the twenty first century due to the disastrous global effects of rising salinity [13]. Salinity deteriorates about two million hectares of world's arable land each year [18]. It is extended to more than 9 billion ha which is a threat to agriculture [19]; and it covers about 20 and 30% of the world's irrigated agriculture and arid and semi-arid regions (which is worse), respectively [20, 21]. Consequently, salinity adversely reduced the growth performance, yield, and productivity of different cultivated crop [22, 23, 24].

In northern Ethiopia; the Tigray region is known for its most abandoned land and drought-prone semi-arid environment. Subsequently, the regional government started to practice intensive irrigated agriculture within the framework of the national strategies since 1994 [8] to sustain its smallholder farmers [25]. Within ten-year intervals, the regional irrigated land has increased from 15,000 ha to more than 243,000 ha [26] resulting in vulnerability to soil salinity due to the intensified irrigation and poor irrigation water management [27, 28, 16].

Based on the relevance and the extent of the topic Ayni-qaqa is comparatively found to be suitable for irrigation. Farmers of the community intensively irrigate their land to produce crops but, the yield has been reduced over time. Even though there have been some localized research on salinization in the dry semi-arid region [29, 30, 31], a thorough investigation is necessary to identify the primary sources of salinity and measure its extent. Hence, knowing these is necessary for understanding and recommending controlling measures to improve agricultural outputs. Determining salinity statuses on a profile basis at which the majority of crops grow is important because it helps recognize whether salt is going down the soil depth or escaping up through capillary rise from the nearby groundwater table. Assessment is essential to provide and present recommendations for decision-makers and irrigation users to increase agricultural production in a sustainable manner and reduce the build-up of salinity in the soil profile. Therefore, this study was carried out targeting quantifying the degree of salinity to understand the status of salinity in the irrigation scheme at Ayni-qaqa.

1.1. Study objectives

- To assess the salinity status of Ayni-qaqa irrigation scheme.
- To indicate salinity variation across sites.
- To indicate salinity variations down a profile.
- To see the difference of salt accumulation during summer and winter.
- To recommend salinity measures.
- To contribute for further researches.

2. Materials and Methods

2.1. Area description

The study was carried out at Ayni-qaqa irrigation scheme (about 100 ha) in Tigray; the semi-arid region in the northern part of Ethiopia. It is located between 13°31'31.28" – 13°31'19.27"N, 39°30'25.16" – 39°30'28.75"E and 13°31'24.77" – 13°31'13.38"N and 39°31'6.15" – 39°31'6.70"E and average elevation of the area is 1970 m.a.s.l in northeast part of Mekelle city.

The agro-ecological zone of Ayni-qaqa is generally categorized as “*weinadega*” ((SM₃) Tepid sub moist mid highland) and categorized under a mono-modal rainfall pattern with mean annual rainfall of 650 mm received during periods between June and September. The annual temperature of the study area ranges between the 18 and 27⁰c. The soil type of the area is dominantly categorized under vertisols which is favorable for production of different crops.

The local community practice mixed-agriculture in which crop and livestock productions are the most economic activities with an unpredictable rainfall and scant vegetation coverage like most part of Ethiopia [32]. The dominant cropping practices are cereal crops production during the rainfed season and horticultural crops during irrigation.

2.2. Data collection and sampling techniques

Spring water which is located on the upper position of the area is used as the main source of irrigation water for the scheme. Considering the irrigation period that the local farmers follow, the Ayni-qaqa irrigation scheme was divided in to four sites for detailed salinity assessment. These are; (i) winter irrigated and rest during summer; (ii) rainfed cereal cultivation during summer and winter irrigation for horticultural crops; (iii) irrigation starting from early August to November; and (iv) both seasons irrigated.

The first site is located in the upper extreme position of the scheme (near to the spring) and due to waterlogging it stays out of any agricultural practice every summer time. This site has a light colored soil that might indicate the existence of salt development. The second site is also located to the side of the spring near to a river and has a black soil which is dominant in the study area. Site three is irrigated starting from early August to November when the potential of the spring water is high enough to reach there. The other irrigation site is also located at the lower extreme position of the study area far from the spring (sources of water).

The spatial variability of salinity assessed based on soil depth determines the severity across the scheme. Soil samples were collected from the four sites which were divided by their irrigation periods for both dry and wet seasons. A total of 128 composite soil samples were collected from the four sites at 15 cm depth interval (0-15, 15-30, 30-45, and 45-60 cm) using augur.

Table 1. Samples collected from each site of the scheme

Sites	Sample size across the four depths			
	0-15 cm	15-30 cm	30-45 cm	45-60 cm
Wet season				
Site-one	3	3	3	3
Site-two	5	5	5	5
Site-three	2	2	2	2
Site-four	5	5	5	5
Dry season				
Site-one	4	4	4	4
Site-two	5	5	5	5
Site-three	3	3	3	3
Site-four	5	5	5	5

2.3. Data analysis

The soil pH and electrical conductivity (EC) values were determined electrometrically using pH meter and electrical meter for the 1:5 soil water extract (EC₅). Calcium (Ca²⁺) and magnesium (Mg²⁺) content of the soils were also analyzed using titration with EDTA using the standard methods. Analyses of these parameters were carried out using laboratory procedures adopted by [33].

Table 2. Laboratory methods used for agricultural soil analysis

Soil parameters	Symbol	Analysis methods used
Alkalinity/basicity	pH	Potentiometer (1:2.5 H ₂ O, v/v)
Electrical conductivity	EC	Conductometry (1:2.5 H ₂ O, v/v)
Calcium	Ca ²⁺	EDTA (0.05 N) titrimetric
Magnesium	Mg ²⁺	EDTA (0.05 N) titrimetric
sodium	Na ⁺	Flame photometric

Source; [33], Soil texture was also determined using the hydrometer method.

Soil analysis for each site of the irrigation scheme was carried out first in the laboratory. Prior to the analysis, all soil samples were submitted to the soil laboratory and next subjected to air-dry at room temperature, crushed, and passed through a 2 mm sieve. The 1:5 soil to water ratio suspensions were prepared by weighing 10 g of soil into a tube, adding 50 ml of deionized water, and shaking for 5 minutes on a shake [34].

Salinity indicator parameters including, pH, EC, Ca²⁺, Mg²⁺ and Na²⁺ as well as soil texture for the collected soil samples were analyzed in the laboratory. The value of these parameters provides a sufficient description of the soil salinity status in the irrigated agriculture [35, 36, 37]. Furthermore, various indicators such as the total dissolved solids (TDS), electrical conductivity (EC), sodium adsorption ratio (SAR), magnesium adsorption ratio (MAR), and Kelly ratio (KR) were used to determine the quality of the soil for agricultural application (Table 5). Different equations for obtaining these indices were also used as indicated below.

1. Total dissolved solutes: Generally, reflects the amount of dissolved minerals content, and this controls its use for use [38, 39]. TDS is in mg l⁻¹ and EC in ds m⁻¹.

$$TDS = EC \times 640 \text{ (when EC} > 5 \text{ ds m}^{-1} \text{ 800 was used instead of 640)} \quad \dots(1)$$

2. Sodium adsorption ratio: Expresses the relative activity of sodium ions in the exchange reactions with the soil and measures the relative concentration of sodium to calcium and magnesium [38, 39].

$$SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{0.5} \quad \dots(2)$$

3. Magnesium adsorption ratio: The MAR value is affected by the concentration of Ca²⁺ and Mg²⁺ in the soil samples [40] (Raghunath, 1987).

$$MAR = Mg^{2+} / (Ca^{2+} + Mg^{2+}) \times 100 \quad \dots(3)$$

4. Kelly ratio: KR used as an indication of sodium concentration in meq l⁻¹ [41].

$$KR = Na^+ / (Ca^{2+} + Mg^{2+}) \quad \dots(4)$$

5. Exchangeable sodium percentage:

$$ESP = 1.5SAR / (0.015 SAR) \dots (5)$$

The measured soil salinity values from the irrigation schemes were compared with the standard threshold values of the parameters (Table 3). The results obtained from the laboratory and indices, the mean of each parameter for each site in the irrigation scheme was derived using descriptive statistics. The t-test was used to compare the parameter mean values between the soil depths for each site.

Table 3. Salinity parameter recommendations made for the soil samples for agricultural uses

Salinity parameters	Unit	Tolerable	Sources
Total Dissolved Solids	mg l ⁻¹	0-2000	[36]
Electrical Conductivity (saturation extract)	ds m ⁻¹	0-4	
Alkalinity/basicity (pH)	0-14	6.5-8.4	“
Calcium	meq l ⁻¹	0-20	“
Magnesium	meq l ⁻¹	0-5	“
Sodium	meq l ⁻¹	0-40	“
Sodium Adsorption Ratio	-	0-9	“
Magnesium Adsorption Ratio	%	<50	[40]
Kelly Ratio	meq l ⁻¹	<1	[42]

3. Result and Discussion

3.1. Quantitative soil Assessment

The salinity status of Ayni-qaqa irrigation scheme was measured from the soil samples collected across all sites of the scheme. The soil samples taken from each soil depth (0-15, 15-30, 30-45, and 45-60 cm) of the root zone were subjected to soil chemical analysis.

3.2. Laboratory analysis for salinity parameters and salinity indices

The findings of laboratory analyses of the different salinity parameters, including pH, EC, and exchangeable cations, were statistically examined. In comparison to the FAO standards [36], the average pH values of the soil samples at each of the four scheme sites are typically below the guidelines recommended for agricultural use in all layers (Table 4-7).

The soil pH values throughout the soil depths in the irrigation scheme ranges from 8.20-7.50 as well as 8.07-7.11 for the wet and dry seasons, respectively. The first site of the irrigation scheme is at a point of approaching the optimum values for all soil depths (Table 4). Generally, when we look in to the pH values of each depth across all sites in the scheme it marks greater than 7 (Table 4-7), showing that the irrigation scheme has a tendency to be alkaline, which may cause salinity [35].

The analysis of soil exchangeable cations (Na⁺, Ca²⁺, and Mg²⁺) concentration following the appropriate procedures described in Table 2 showed that the mean values of Ca²⁺ and Na⁺ from each site in the scheme are under the standards prescribed for irrigation use for all depths [36]. However, some variations were observed for the mean

values of Mg^{2+} (Table 4-7). For instance, considering the inconsistent trend in the other sites the value of Mg^{2+} concentration at site four is above the standards to use for irrigation across all depths during both seasons. The maximum Mg^{2+} concentration at 45-60 cm depth of site four is 10.52 meq l^{-1} , which is greater than double of the acceptable limit. There was also a tendency of high Ca^{2+} concentration than the standard threshold for the 30-45 cm depth of site-one (Table 4).

Furthermore, as shown in Tables 4 and 7, site one and site four showed grater average electrical conductivity (EC) and total dissolved solutes (TDS) which are above the recommended standards for irrigation [43] across all depths in the scheme. The EC and TDS measured for the scheme stretched to 6.76 ds m^{-1} and 5408 mg l^{-1} in the 15-30 cm depth of site four during dry season whilst minimum is 3.25 ds m^{-1} and 2080 mg l^{-1} in the 30-45 cm depth for site two similarly during dry season, respectively (Table 4). The EC of the soil in site one shows a decreasing trend down the soil depth for both seasons with some inconsistencies (figure 1 (a)).

Table 4. Soil chemical properties for site-one of the scheme

Depth	EC(ds m ⁻¹)	pH	Ca ²⁺ (meq l ⁻¹)	Mg ²⁺	Na ⁺	TDS (mg l ⁻¹)	SAR	MAR %	ESP	KR (meq l ⁻¹)
Wet Season										
0-15	5.08	8.13	16.54	4.76	15.55	4064.00	4.77	22.35	6.47	0.73
15-30	4.92	8.05	19.50	4.66	18.76	3148.80	5.40	19.29	7.36	0.78
30-45	5.00	8.03	17.18	3.15	16.22	3200.00	5.10	15.49	6.95	0.80
45-60	4.58	7.97	18.92	5.16	17.14	2931.20	4.94	21.43	6.74	0.71
Dry Season										
0-15	5.72	7.72	19.30	5.02	18.24	4576.00	5.23	20.64	7.26	0.75
15-30	6.00	7.43	17.88	6.23	16.10	4800.00	4.64	25.84	6.54	0.67
30-45	4.89	7.25	20.09	4.57	19.09	3129.60	5.44	18.53	6.22	0.77
45-60	4.85	7.56	18.96	5.25	16.69	3104.00	4.80	21.69	6.73	0.69

Soils having EC values greater than 4 ds m^{-1} and TDS greater than 2000 mg l^{-1} are considered as saline [36]. Accordingly, laboratory analysis results showed that site one, site four, and some depths of site three have shown possible salinity development. Hence, agricultural lands in these sites of the scheme are becoming non-productive, because soils are getting abandoned by salinity. The salinity occurrence could be the due to availability of salinity encouraging parent materials in the soil depths and inappropriate irrigation water management.

Table 5. Soil chemical properties for site-two of the scheme

Depth	EC(ds/m)	pH	Ca ²⁺	Mg ²⁺	Na ⁺	TDS	SAR	MAR	ESP	KR
Wet Season										
0-15	3.61	7.85	19.55	4.95	36.66	2310	13.37	20.20	16.75	1.50
15-30	3.29	7.79	8.13	4.22	34.04	2106	13.38	34.17	16.73	2.76
30-45	3.72	7.82	9.74	4.98	35.98	2381	13.30	33.83	16.63	2.44
45-60	3.80	7.66	7.78	5.17	34.11	2432	13.40	39.92	16.67	2.63
Dry Season										
0-15	3.90	7.61	10.19	3.03	35.21	2496	13.70	22.92	16.98	2.66
15-30	3.79	7.50	11.29	3.00	34.85	2426	13.04	20.99	16.35	2.44
30-45	3.25	7.55	10.43	4.15	38.12	2080	14.12	28.46	17.50	2.61
45-60	3.51	7.40	9.77	5.24	37.46	2246	13.67	34.91	16.94	2.50

The dominant irrigation water conveyance structures in the Tigray region (particularly the scheme) are traditional surface canal irrigation systems; which lacks proper design that promote the occurrence of salinity in the irrigation scheme [16]. These methods also lack design standards based on the characteristics of the water potential and area coverage which could also be a motive for salinity development in the irrigation scheme.

The salinity of the irrigation scheme was also estimated based on some salinity indices such as SAR, MAR, and KR. The highest soil SAR value (4326) was obtained from site four in the 0-15 cm depth while the lowest was 2080 from 30-45 cm depth of site tow. Generally, the mean values of SAR of the soil of each irrigation site in the scheme are beyond the acceptable range for irrigation purposes across all depths (Table 4-7).

The MAR value is affected by the concentration of calcium and magnesium in the soil. Calcium and magnesium often make a state of equilibrium in the soil solution [44]. Crop production is difficult when the MAR value is greater than 50% [40, 45] (Table 3). Hence, since the MAR results of the irrigation scheme for the all depths show an average value below the maximum permissible limit (Table 4-7), salinity effects related to magnesium concentration in the irrigation sites of the scheme are uncommon.

The soil or water of an area can be used for irrigation purposes if the average Kelly ratio (KR) values of a given scheme have values less than one [42] (Table 3). The average KR values of the soil collected from sites one and four in the scheme are below the standards to use for irrigation. However, exceptions occurred for sites two and three in all depths which exceeded the optimum recommendation for irrigation use (Table 5 and 6). The KR values of the soils range from 0.67 to 2.76 meq l⁻¹ from site one and site two, respectively.

Except for site one the EC value of the scheme relatively increases down the soil profile which shows leaching is dominant over capillary salinization during the wet season while decreasing for the dry season (Figure 1 (a-d)). The increasing salinity trend down the soil depth might be due to the reason that leaching soluble salts by deep percolation had been relatively dominant compared to upward movement of salts by capillary rise. In contrast, the decreasing soil salinity down the soil profile in the dry season might be due to the dominance of capillary salinization as compared to any potential leaching.

Additionally, the calculated ESP value can be used to determine whether the soil is saline or not. Therefore, according to the United States Salinity Laboratory [46], sites one and four are classified as saline soil due to the lower ESP (< 15) coupled with the higher EC (> 4 ds m⁻¹) values during both seasons. However, soil of site two in both seasons and site three especially at the surface (0-30 cm depth) during the wet season are classified under sodic soils (EC< 4 ds m⁻¹ and ESP> 15). As can be seen in Tables 5 and 6 the dominant cation in both sites is sodium followed by calcium. During the dry season, the local farmers supplement their vegetables from the flowing stream nearby, that's why the level of salinity reduced during that season.

Table 6. Soil chemical properties for site-three of the scheme

Depth	EC(ds/m)	pH	Ca ²⁺	Mg ²⁺	Na ⁺	TDS	SAR	MAR	ESP	KR
Wet Season										
0-15	3.35	7.86	10.00	4.00	34.17	2144	12.92	28.57	16.23	2.44
15-30	3.78	7.93	10.94	3.97	34.00	2419	12.45	26.63	15.74	2.28

30-45	4.21	7.89	9.81	4.46	31.45	2694	11.78	31.25	15.00	2.20
45-60	4.68	7.83	8.29	5.06	29.01	2995	11.23	37.90	14.90	2.17

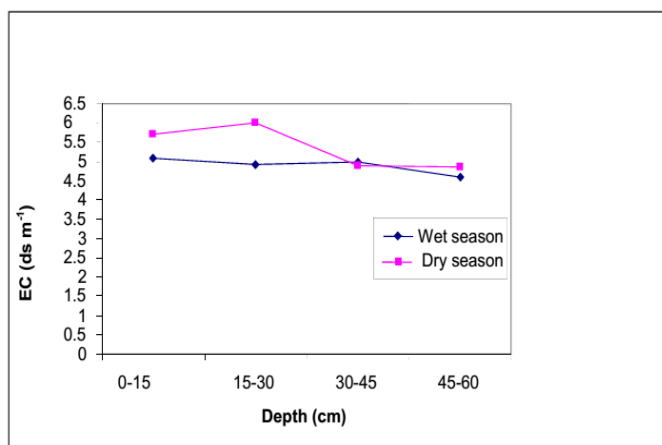
Dry Season

0-15	5.20	7.39	8.40	4.61	29.06	4160	11.40	35.43	14.61	2.23
15-30	4.73	7.42	9.18	3.40	27.14	3027	10.80	27.03	13.97	2.16
30-45	3.63	7.58	7.27	5.12	31.25	2323	12.56	41.32	15.83	2.52
45-60	3.45	7.11	9.94	5.62	32.34	2208	12.42	36.12	15.66	2.08

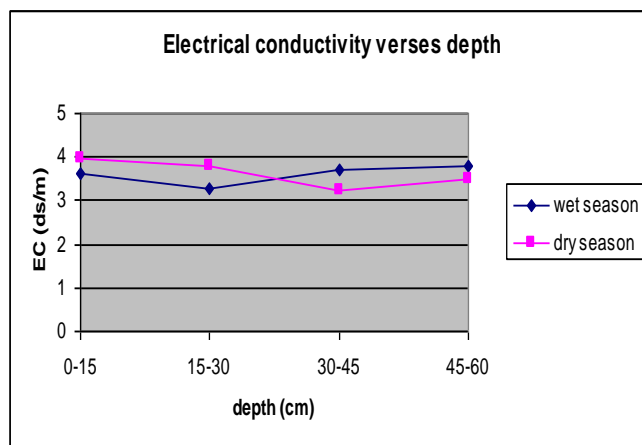
The presence of salinity in the irrigation system is generally revealed by the results produced from the various indicators and those received directly from the laboratory. It is evidenced that the agricultural soil in the scheme comprises a significant amount of dissolved salts. The highest soil salinity development was observed in site four (Table 7) as compared to the other parts of the scheme that might be due to the intensive irrigation during both seasons. Therefore, salinity stress can affect most of the irrigated crops due to the high salt concentration in the root zone, because all plants grown in the area have shallow root depths (below 60 cm). Subsequently, crop productivity would be highly reduced due to the limited crop growth. Therefore, the salinity effects on the plant growing root zone can be reduced by adequate leaching and adding amending means like gypsum [39].

Table 7. Mean values of soil chemical properties for site-four in the scheme

Depth	EC(ds m ⁻¹)	pH	Ca ²⁺	Mg ²⁺	Na ⁺	TDS	SAR	MAR	ESP	KR
Wet Season										
0-15	5.24	8.12	15.64	5.67	19.67	4192	6.03	26.61	8.34	0.92
15-30	5.72	8.15	18.09	5.66	18.00	4576	5.22	23.83	7.25	0.76
30-45	6.15	7.51	16.78	4.51	15.29	4920	4.69	21.18	6.54	0.72
45-60	6.33	8.20	14.29	7.16	16.18	5064	4.94	33.38	6.93	0.75
Dry Season										
0-15	6.76	8.07	13.90	6.02	17.24	5408	5.46	30.22	7.57	0.87
15-30	6.66	7.67	12.88	7.32	18.10	5328	5.70	36.24	7.84	0.90
30-45	5.90	7.11	14.09	9.75	19.09	4720	5.53	40.90	7.66	0.80
45-60	5.68	7.51	11.89	10.52	20.96	4544	6.26	46.94	8.58	0.94



(a)



(b)

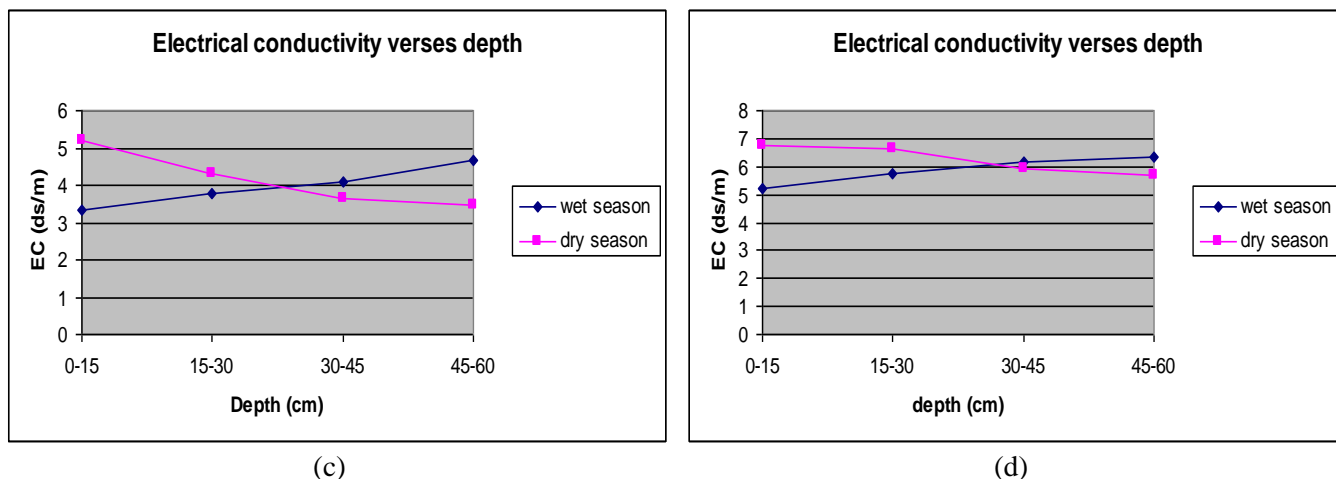


Figure 1. The trend of salinity across the scheme for site-one to site-four (a-d), respectively for the dry and wet seasons

4. Conclusion and Recommendation

Soil health and water quality are the major factors influencing the sustainability of irrigation agriculture in the dry arid and semi-arid regions. These precious resources are vulnerable to varying degrees and severity of salinity different irrigation schemes of Tigray. The current intensification of irrigation agriculture practices has resulted in an expansion of salt-affected soils in irrigation schemes. However, the extent and expansion or progress of soil salinity in the scheme is to be studied. According to the result of this study salinity status of soil in most parts of the scheme is above the acceptable recommended standards for irrigation use. The soil samples taken from sites one and four have higher salinity levels. Poor irrigation management, inadequate use of amendments, drainage practices such as leaching, and the parent material beneath the surface are the major causes of salinity in the irrigation scheme.

Therefore, community-based participatory salinity management strategies that involve the local farmers, extension workers, and some stakeholders by creating awareness and common sense towards ownership could possibly be useful to counter the salinity problems and overwhelming developments of irrigated agriculture. Finally, irrigation users and decision-makers should consider promising controlling measures to reduce salinity build-up thereby increasing agricultural production in a sustainable way.

Some future suggestions to solve the salinity problems:

- Leaching with salt free irrigation water.
- Planting salinity resistant crops.
- Fallowing, mulching and cover crops.
- Organic fertilizer amendments.

Declarations

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Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors made an equal contribution in the Conception and design of the work, Data collection, Drafting the article, and Critical revision of the article. Both the authors have read and approved the final copy of the manuscript.

Availability of data and material

Authors are willing to share data and material according to the relevant needs.

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